DESIGN OF ANTIPROTON ELECTRON COOLING IN THE RECYCLER

A. Burov, J. MacLachlan, J. Marriner and S. Nagaitsev, FNAL, Batavia, IL

Abstract

A conceptual design of electron cooling of 9 GeV antiprotons for the Tevatron is discussed. Analytic and numeric calculations of the cooling process determine the basic requirements of the cooler.

1 PURPOSE

During a Tevatron store, emittances of the colliding bunches grow and the luminosity decreases. For RUN II, the luminosity is calculated to drop by a factor of 2 after 6-7 hours [1], so the beams should be renewed after this time. The purpose of the Recycler storage ring is to accept the unspent antiprotons ($\bar{p}$) from the Tevatron, to recool them transversely and longitudinally, and to redeliver them to the collider. The Recycler must also accept fresh antiprotons from the Accumulator, and this process requires longitudinal cooling too. For RUN II, the stochastic cooling system is thought to be adequate; an example of simulations for the transverse cooling is shown in Fig. 1.

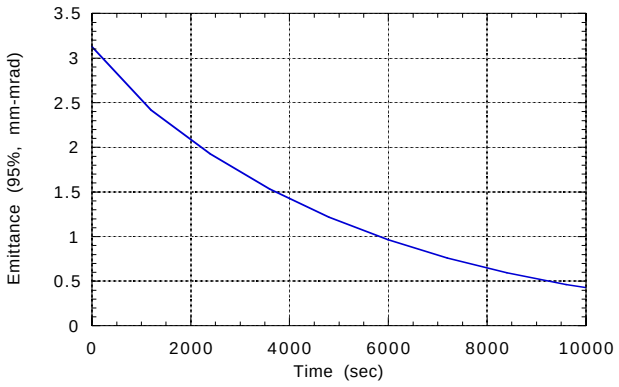

Figure 1: Evolution of the (unnormalized) emittance of $5 \cdot 10^{12}$ particles in the Recycler with the full momentum spread $\pm 2 \cdot 10^{-3}$ during stochastic cooling with 2-4 GHz bandwidth.

However, the efficiency of the stochastic cooling decreases with intensity of the cooled beam, which could make it insufficient for the future TeV 33 program. Electron cooling might be a good supplement to stochastic cooling because of its independence on the beam intensity. On the other hand, electron cooling is much more efficient if the beam is already precooled. Thus, a hybrid cooling scheme could be used in the Recycler, with stochastic cooling for the first stage and electron cooling for the second.

2 SCENARIO

A possible scenario for the periodic cooling-stacking process in the Recycler could be following:

- $t = 0$: 100 bunches of (hot) antiprotons leave the Tevatron, are decelerated in the Main Injector, and arrive at the Recycler, sharing its circumference with already cooled antiproton beam. Then, the cold portion is transfered to the Main Injector, releasing the phase space for the hot beam with $N = (2.5 - 10) \cdot 10^{12}$ $\bar{p}$'s occupying $\mathcal{A} = 400$ eVs of the longitudinal phase space and 30π mm mrad of the normalized 95% emittance. Transverse stochastic precooling starts.
- Every quarter of an hour, a fresh pbar batch arrives from the Accumulator. Its population is 10^{11} in 10eVs and 15π mm mrad (normalized 95%). It is adjoined longitudinally to the whole stack by means of the barrier-bucket technique [2].
- $t = 1-2$ h: Stochastic precooling finishes; beam emittance is 15πmm mrad. Electron cooling begins.
- $t = 3 - 8$ h: Electron cooling finishes producing a beam with 10π emittance and 150 eVs or less of the longitudinal phase space. The cycle is then repeated.

3 SIMULATION RESULTS

To simulate electron cooling processes, a multi-particle C++ code has been written. This code tracks the time evolution of an ensemble of cooled particles, optimizes the cooling process under various conditions and finds the tolerances on imperfections.

In distinction to usual situation in low-energy coolers, relative velocities between the cooled particles and the electrons are supposed here to be determined by the cooled particle ($\bar{p}$) velocities. Electron velocities are assumed to be low enough not to depress the cooling rates. In this case, the longitudinal and transverse cooling rates $\lambda_\parallel$ and $\lambda_\perp$ are strong functions of the $\bar{p}$ longitudinal and transverse velocities in the beam frame $v_\parallel$ and $v_\perp$ [3]:

$$\lambda_\parallel \propto (v_\perp^2 v_\parallel)^{-1}, \quad \lambda_\perp \propto v_\perp^{-3} \quad \text{for } v_\parallel \leq v_\perp.$$

The smaller the $\bar{p}$ velocity is, the faster it decreases. Thus, electron cooling tends to shape a narrow core of supercooled particles inside the distributions. For flat pbar distributions, i.e., $v_\parallel \ll v_\perp$, the longitudinal rates are higher than the transverse and the longitudinal core is created first. Actual size of this core is determined by an equilibrium between cooling and IBS diffusion which is calculated separately (see section 5). The evolution of the recycled $\bar{p}$'s from the initial state is shown in Figs. 2 and 3.

0-7803-5573-3/99/$10.00@1999 IEEE.

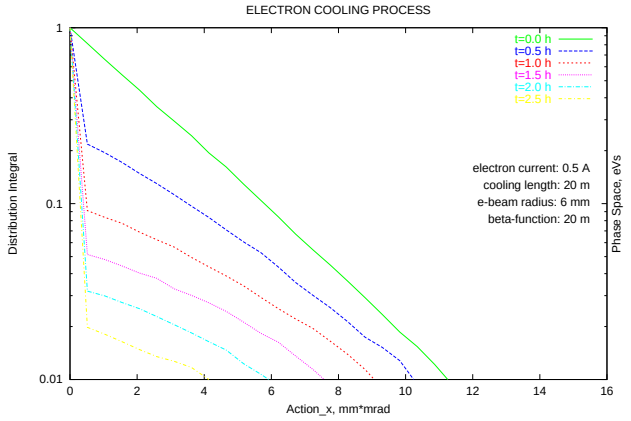

Figure 2: Evolution of the transverse $\bar{p}$ distribution from the initial Gaussian one with the rms normalized emittance 2.5 mm mrad.

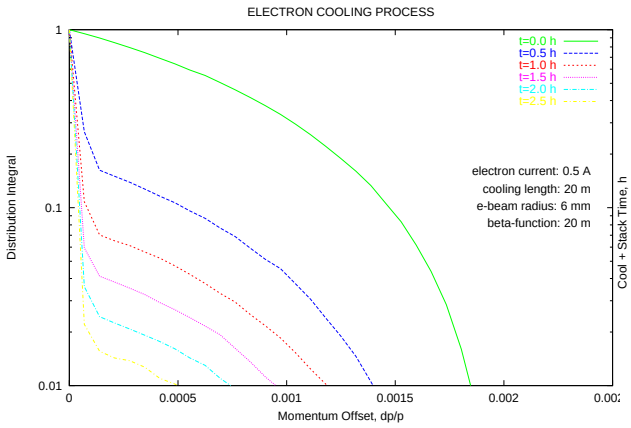

Figure 3: Evolution of the $\bar{p}$ momentum distribution from an initial parabolic one.

The conclusion from the simulations is that transverse cooling of the recycled $\bar{p}$'s from $\epsilon = 15\pi$ mm mrad to $\epsilon = 10\pi$ mm mrad requires 0.9 Ampere×hour (Ah) of (cooler length)×(cooling time), for a 20 m cooling section. For beam from the Accumulator, this value is 0.7 Ah.

The longitudinal phase area $\mathcal{A}$ shrinks with a rate $r_0 \approx 1.2$ A^{-1}h^{-1} over the whole interesting interval 150 eVs $< \mathcal{A} <$400 eVs. This approximate rate is used in the stacking model discussed below.

4 COOLING-STACKING PROCESS

The phase space evolution in the cooling-stacking process can be described as:

$$\dot{\mathcal{A}} = -r_0\mathcal{A} + f_s\mathcal{A}_b + f_s\Delta_s\mathcal{A}$$

where f_s is the stacking frequency, the number of injections per hour, $\mathcal{A}_b$ is the batch phase area, and Δ_s is the fractional

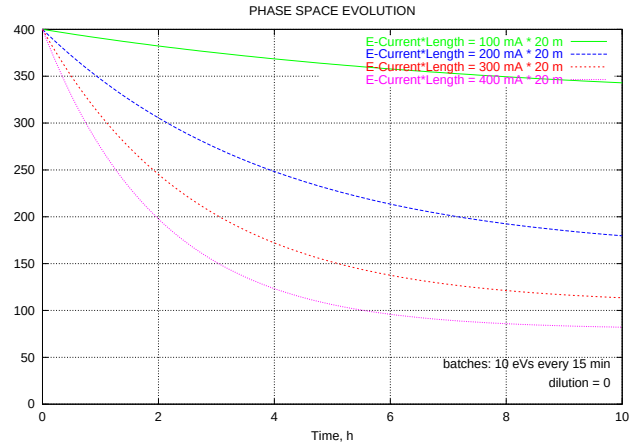

Figure 4: Evolution of the longitudinal phase space area in the cooling-stacking process

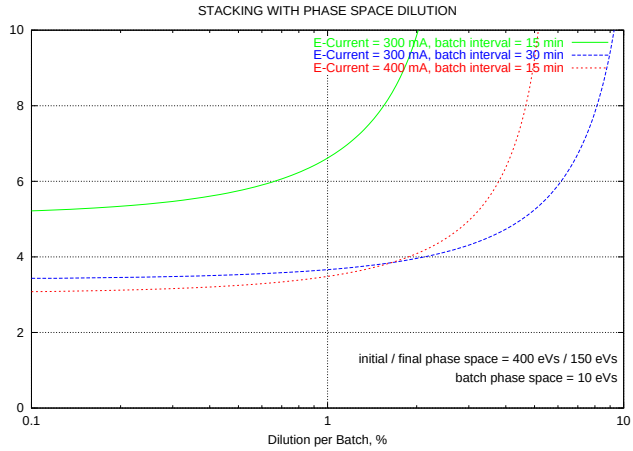

Figure 5: Tolerances on the longitudinal phase space dilution due to the stacking imperfection.

phase area dilution due to the stacking imperfection. The solution reads:

$$\begin{aligned} \mathcal{A}(t) = &\quad \mathcal{A}(\infty) + (\mathcal{A}(0) - \mathcal{A}(\infty))\exp(-(r_0 - f_s\Delta_s)t) \\ \mathcal{A}(t) \to &\quad \mathcal{A}(\infty) = \mathcal{A}_b f_s/(r_0 - f_s\Delta_s) \end{aligned} \tag{1}$$

The asymptotic phase space area $\mathcal{A}(\infty)$ is related to an equilibrium between factors which tend to increase the phase space (stacking, dilution) and the factor tending to shrink it (cooling). The phase area evolution is presented in Fig. 4, a tolerance for the dilution can be found from the results shown in Fig. 5. The conclusion is that for the injection frequency $f_s = 4h^{-1}$ and dilution $\Delta_s < 1\%$, the current $I_e = 300$ mA is sufficient for antiproton accumulation.

5 INTRA-BEAM SCATTERING OF ANTIPROTONS

Intra-beam scattering (IBS) calculations are simplified by assuming that first, the longitudinal $\bar{p}$ velocities are smaller than transverse (typical for hadron beams), and second, beam envelope variations are small enough (about 30% in the Recycler) to apply the smooth approximation.

Under these assumptions, IBS is reduced to a heat transfer from the hot transverse degrees of freedom to the cold longitudinal one which can be described as a diffusion in the longitudinal degree of freedom. The diffusion imposes a limit on the width of the longitudinal distribution: it cannot be smaller than the one determined by the cooling-diffusion equilibrium. If the equilibrium width is smaller than the design value, IBS can be neglected; otherwise, IBS puts a limit on the final width of the distribution.

Conventionally, the IBS diffusion coefficient is calculated as a single number for the whole distribution. This number results from an averaging of the local diffusion coefficient, which depends on actions of the scattered particle, over the distribution. However, to derive the equilibrium distribution with a good accuracy, a knowledge of the average diffusion is not sufficient; more detailed information contained in the local diffusion dependencies is required. The diffusion coefficient D as a function of velocity amplitudes v_x, v_y of the given particle which scatters on other particles distributed with rms velocity $v_\perp$ is calculated from the Landau collision integral [3]. For a Gaussian transverse distribution

$$D = \frac{4\pi n_{\bar{p}} r_p^2 L_{\bar{p}}}{\gamma^2\beta^2 v_\perp}\mathcal{I}, \quad v_\perp = \sqrt{\frac{\gamma\epsilon_n}{\beta_f}}$$
$$\mathcal{I} = \frac{2}{\pi}\frac{v_\perp^3}{\sqrt{(v_x^2+v_y^2+2v_\perp^2/\pi)(v_x^2+2v_\perp^2/\pi)(v_y^2+2v_\perp^2/\pi)}} \tag{2}$$

where $n_{\bar{p}}$ is the pbar density at the beam axis, $L_{\bar{p}}$ is the IBS Coulomb logarithm and ϵ_n is the normalized rms emittance. The calculated diffusion is consistent with the average diffusion coefficient reported in [4] to an accuracy better than 10%; it is also consistent with numerical calculations of the average diffusion that are free from the above simplifications [5].

The evolution of the longitudinal distribution is described by the Fokker-Planck equation:

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial w}\left(Ff + \frac{D}{2}\frac{\partial f}{\partial w}\right); \quad w = \delta p/p. \tag{3}$$

Here

$$F = \frac{8(I_e/e)r_e r_p \eta L_\parallel}{\pi\beta^2\gamma^2 a^2 v_x v_y} \tag{4}$$

is the cooling force independent in this case of the value of the longitudinal velocity w, with I_e as the electron current, a as the electron beam radius, η as the circumference fraction occupied by the cooler and $L_\parallel$ as the Coulomb logarithm for the longitudinal cooling [3].

The Fokker-Planck equation (3) with the diffusion coefficient (2) and the cooling force (4) can be analytically resolved for the equilibrium distribution:

$$f = \exp(-w/\bar{w})/\bar{w}, \quad \bar{w} = D/2F,$$

yielding the equilibrium longitudinal phase space (95%) averaged over the transverse distribution

$$\mathcal{A} = \frac{1}{4}\frac{I_{\bar{p}}}{\eta I_e}\frac{r_p}{r_e}\frac{L_{\bar{p}}}{L_\parallel}\frac{a^2}{a_{\bar{p}}^2}ET_0.$$

This phase space is sufficiently small; for $N_{\bar{p}} = 1\cdot 10^{13}$ and $I_e = 300$ mA, $\mathcal{A} = 30$ eVs. As long as the desired phase space area is larger than this equilibrium, the IBS may be neglected.

The main parameters of the electron cooling in the Recycler for the 100 bunch scenario are summarized in Tab. 1.

Table 1: Electron Cooling for 100 Bunches

Parameter	**Value**
Circumference	3319.4 m
Pbar momentum	8.9 Gev/c
Number of pbars, total	$(5-10)\cdot 10^{12}$
Init. long. area recycled pbars	400 eVs
Fin. long. 98% area, goal	150 eVs
Init. norm. 95% emittance	30π mm mrad
Fin. norm. 95% emittance	10 π mm mrad
Batches per hour	4 h^{-1}
Batch area	10 eVs
Batch norm. 95% emittance	15 π mm mrad
Cooling length	20 m
Beta-function in the cooler	20 m
Electron current	300 mA
Time of cool-stack cycle	7 hour
Electron beam radius	0.6 cm
Electron angle	$\leq 80\,\mu$rad
Electron temperature	≤ 1 eV
Electron momentum spread	$\leq 5\cdot 10^{-5}$

The authors are thankful to Ya. S. Derbenev and V. V. Parkhomchuk for fruitful discussions.

6 REFERENCES

[1] G. Jackson, ed. "Fermilab Recycler Ring, TDR", Apr. 1996.

[2] J. Griffin et al., IEEE Trans Nucl. Sci. **NS-30**, p. 3502 (1983).

[3] A. Burov, J. MacLachlan, "Optimization of Electron Cooling for a Medium Energy Accumulator Ring", submitted to NIM A.

[4] V. Lebedev et al., "Single and Multiple Intrabeam Scattering in a Laser Cooled Beam" NIM A **391**, p. 176 (1997).

[5] P. Colestock, private communication.